TRANSIENT LOW-MASS X-RAY BINARIES IN QUIESCENCE

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We summarize the quiescent X-ray observations of transient low-mass X-ray binaries. These observations show that, in quiescence, binaries containing black holes are fainter than those containing neutron stars. This has triggered a number of theoretical ideas about what causes the quiescent X-ray emission. For black hole binaries, the options are accretion onto the black hole or coronal emission from the rapidly rotating stellar companion. There are more possibilities for the neutron stars; accretion, thermal emission from the surface or non-thermal emission from a "turned-on" radio pulsar. We review recent theoretical work on these mechanisms and note where current observations can distinguish between them. We highlight the re-analysis of the quiescent neutron star emission by Rutledge and collaborators that showed thermal emission to be a predominant contributor in many of these systems. Our knowledge of these binaries is bound to dramatically improve now that the *Chandra* and *XMM-Newton* satellites are operating successfully,

1. Introduction

Many black holes and neutron stars are in binaries where a steady-state accretion disk (one that supplies matter to the compact object at the same rate as mass is donated from the Roche-lobe filling companion) is thermally unstable (Van Paradijs 1996; King et al. 1996). This instability results in a limit cycle – as in dwarf novae (where the compact object is a white dwarf) – with matter accumulating in the outer disk for months to decades until a thermal instability is reached (Huang & Wheeler 1989; Mineshige & Wheeler 1989) that triggers rapid accretion onto the compact object. The substantial brightening in the X-rays (typically to levels near the Eddington limit, $10^{38} - 10^{39}$ erg s^{-1} for $M = 1 - 10 M_\odot$ stars) brings attention to these otherwise previously unknown binaries. Both neutron stars (NS) and black holes (BH) exhibit these X-ray outbursts, separated by periods ($\sim$ months to decades) of relative quiescence (for recent reviews of the outburst properties, see Tanaka & Lewin 1995; Tanaka & Shibazaki 1996; Chen et al. 1997). The neutron stars are identified by Type I X-ray bursts from unstable thermonuclear burning on their surfaces. For those that "appear" to be black holes (based on their spectral and/or timing properties and lack of Type I bursts), detailed optical spectroscopy in quiescence is undertaken. Many of the measured optical mass functions are in excess of the maximum possible neutron star mass ($\approx 3 M_\odot$), making these binaries an excellent hunting ground for black holes (see McClintock 1998 for a summary).

Our purpose is to discuss the X-ray emission from these binaries when they are in their faint "quiescent" state between outbursts. X-ray observations with sensitive pointed instruments (ROSAT and ASCA) of these transients in quiescence have detected all of those harboring neutron stars and some that contain black holes. It is clear that, on average, the binaries containing black holes are less luminous than those with neutron stars (Barret et al. 1996; Narayan et al. 1997a; Asai et al. 1998). It is still a mystery as to what powers the very faint X-ray emission ($L_x \ll 10^{35}$ erg s^{-1}) from these binaries when in quiescence, and we will review the possibilities here.

Accretion is the most often discussed energy source and clearly powers the dwarf novae (the analogous systems that contain white dwarfs in systems with orbital periods typically less than three hours) in quiescence. These were found by *Einstein* to be faint X-ray sources ($10^{30} - 10^{32}$erg s^{-1}) when in their quiescent state (Cordova & Mason 1984; Patterson & Raymond 1985). The inferred accretion rate onto the white dwarf is a few percent of the rate being transferred within the binary, and the X-rays originate from the boundary layer near the white dwarf (Patterson & Raymond 1985). This was confirmed via eclipse observations with ROSAT of three short orbital period DN in quiescence (Mukai et al. 1997; Van Teeseling 1997; Pratt et al. 1999). In all of these systems, the X-ray emission was eclipsed when the white dwarf was behind the companion. The physics that sets this low inflow rate towards the white dwarf is not clear and might well be different than in the binaries containing neutron stars and black holes, which are the focus of this review.

2. Black Hole Transients in Quiescence: Advection Dominated Accretion Flows or Coronal Emission?

At this time, three BHs have been detected in quiescence: A0620−00 (McClintock et al. 1995), GS 2023+33 (Verbunt et al. 1994; Wagner et al. 1994), and GRO J1655−40 (Hameury et al. 1997). The puzzle of the emission mechanism began when ROSAT/PSPC detected X-rays from A0620−00 at a level $L_x \approx 6 \times 10^{30}$ erg s^{-1} (McClintock et al. 1995). McClintock et al. (1995) made it clear that this X-ray emission could not be due to a steady-state accretion disk around the black hole, as if so, there would be a production of optical and UV photons from the outer parts of the disk that would far exceed that observed.

To solve this puzzle and to explain the higher quiescent luminosities ($10^{32} - 10^{33}$ erg s^{-1}) of the transient NSs, Narayan et al. (1997b) invoked an advection-dominated accretion flow (ADAF) onto the compact object at a rate $\dot{M}_q$ in quiescence. For the black holes, the X-rays are produced via Compton up-scattering of the optical/UV synchrotron emission from the inner parts of the flow. The model predicts X-ray emission as a fraction of the optical/UV emission (in excess of that from the stellar companion) – an observable ratio which is used to evaluate the model's success. Current ADAF spectral modeling of the X-ray detected BH's requires that $\dot{M}_q$ be $\sim 1/3$ of the total mass transfer rate in the binary (Narayan et al. 1997a). Accretion rates this high are required because of the relative inefficiency of the flow at producing X-rays (Narayan et al. 1997b; Hameury et al. 1997). The much higher efficiency (by 3-4 orders of magnitude) of X-ray production from accretion onto a neutron star forces the quiescent accretion rate onto these objects to be much lower than for the black holes. In other words, if the implied $\dot{M}_q$ from BHs was landing on a NS, it would shine in quiescence at about 10^{36} erg s^{-1}, a factor of 1000 brighter than observed. A solution is to just dial $\dot{M}_q$ to be uniformly lower in the NS systems than in the BH systems; though this is not easy to do (Menou et al. 1999).

Another possible mechanism for the faint emission from black hole binaries is coronal X-ray emission from the tidally locked companion star (Verbunt 1996; Bildsten & Rutledge 2000). The analogous systems are tidally locked stars in tight binaries, such as the RS CVn systems. These have X-ray luminosities from coronal activity that reach the level observed from the black hole transients. For a convective star that is rotating rapidly, most X-ray observations point to $L_x/L_{\rm bol} \approx 10^{-3}$ as a "saturation limit" in coronal X-ray emission (Vilhu & Walter 1987; Singh et al. 1999).

In Fig. 1, we display the X-ray detections and upper-limits for several observed BH systems, with their optically-derived bolometric flux, along with this saturation limit in $L_x/L_{\rm bol}$, and the prospects of detecting coronal X-rays from undetected systems with *Chandra* (X-ray flux limits for *XMM*-

Newton are about a factor three of lower). Of the previously undetected sources, only GS 2000+25 stands out as a possible new detection of stellar coronal emission (the companion of 4U 1543−47 is not convective, and thus no coronal emission is expected).

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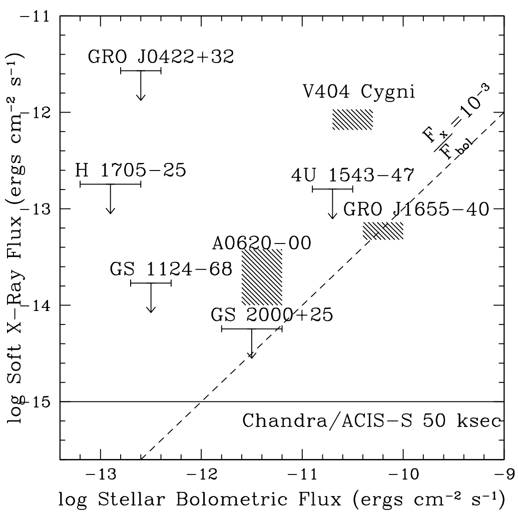

Figure 1. X-ray flux vs. stellar bolometric flux for X-ray detected black hole binaries (shaded regions) and 2σ upper-limits. The dashed line shows a typical coronal value $F_x/F_{\rm bol}$=10^{-3}. The bottom line is the *Chandra*/ACIS-S 50 ksec detection limits for a $N_{\rm H}$=0.2×10^{22} cm^{-2}, Raymond-Smith model at kT=1.0 keV. Detection of X-rays from GRO J0422+32, GS 1124-68, and H 1705−25 with *Chandra* would be well above that expected from coronal emission. GS 2000+25 is close to the $L_x/L_{\rm bol}$=10^{-3} limit and may be detected. While 4U 1543−47 is apparently well within X-ray detectable range, the early-type companion (A2V) is non-convecting, which makes it a "clean" system to study X-ray emission which is not coronal. From Bildsten & Rutledge (2000).

Distinguishing between these two competing mechanisms – ADAFs and coronal emission – can be done with high S/N X-ray spectroscopy across the 0.1-4.0 keV energy range, where the X-ray emission is detected. Stellar coronal X-ray spectra are measured in low-mass stars and are reasonably well described as a Raymond-Smith plasma (Raymond & Smith 1977). These X-ray spectra are distinct from those calculated from ADAFs, which consist of a featureless continuum from the Compton-scattered optical/UV emission and weak line emission that does not appear detectable with the current generation of detectors (Narayan & Raymond 1999).

3. X-Ray Spectra of Quiescent Neutron Stars

Centaurus X-4 was the first NS transient detected in quiescence (Van Paradijs et al. 1987). More recently, quiescent X-ray spectral measurements have been made of Aql X−1 (Verbunt et al. 1994) and 4U 2129+47 (Garcia & Callanan 1999) with the *ROSAT*/PSPC; of EXO 0748−676 with Einstein IPC (Garcia & Callanan 1999); and of Cen X−4 and 4U 1608−522 with *ASCA* (Asai et al. 1996b). The X-ray spectrum of Aql X−1 (0.4–2.4 keV) was consistent with a blackbody (BB), a bremsstrahlung spectrum, or a pure power-law (Verbunt et al. 1994). For 4U 1608−522, the spectrum (0.5–10.0 keV) was consistent with a BB ($kT_{\rm BB} \approx 0.2$–0.3 keV), a thermal Raymond-Smith model ($kT = 0.32^{+0.18}_{-0.5}$ keV), or a very steep power-law (photon index 6^{+1}_{-2}). Similar observations of Cen X−4 with *ASCA* found its X-ray spectrum consistent with these same models, but with an additional power-law component (photon index ≈ 2.0) above 5.0 keV (recent observations with *BeppoSAX* of Aql X−1 in quiescence also revealed a power-law tail; Campana et al. 1998b). These high energy power-law components are not fully understood, and their relationship to the thermal component is unclear. We discuss this more in §4.3.

In four of these five sources (the exception being EXO 0748−676), BB fits implied an emission area with a radius ≈ 1 km, much smaller than a NS. This has little physical meaning however, as the emitted spectrum from a quiescent NS atmosphere with light elements at the photosphere is far from a blackbody (Romani 1987). For a weakly-magnetic ($B \leq 10^{10}$G) pure hydrogen or helium [1] atmosphere at effective temperatures $kT_{\rm eff} \lesssim 0.5$ keV the opacity is dominated by free-free transitions (Rajagopal & Romani 1996; Zavlin et al. 1996). Because of the opacity's strong frequency dependence ($\propto \nu^{-3}$), higher energy photons escape from deeper in the photosphere, where $T > T_{\rm eff}$ (Pavlov & Shibanov 1978; Romani 1987; Zampieri et al. 1995). Spectral fits near the peak and into the Wien tail (which is the only part of the spectrum sampled with current instruments) with a BB curve then overestimate $T_{\rm eff}$ and underestimate the emitting area, by as much as two orders of magnitude (Rajagopal & Romani 1996; Zavlin et al. 1996).

Rutledge et al. (1999; 2000) showed that fitting the spectra of quiescent NS transients with realistic atmospheric models yielded emitting areas consistent with a 10 km radius NS. In Fig. 2, we compare the measured H

[1] The strong surface gravity will stratify the atmosphere within ∼ 10 s (Alcock & Illarionov 1980; Romani 1987). Hence, for accretion rates $\lesssim 2\times10^{-13} M_\odot\,{\rm yr}^{-1}$ (corresponding to an accretion luminosity $\lesssim 2\times10^{33}$ erg s^{-1}), metals will settle out of the photosphere faster than the accretion flow can supply them (Bildsten, Salpeter, & Wasserman (1992)). As a result, the photosphere should be nearly pure hydrogen if $\dot{M}_q$ is small.

atmosphere and blackbody spectral parameters for the quiescent NSs. The emission area radii are larger from the H atmosphere spectra by a factor of a few to ten, and are consistent with the canonical radius of a NS. There is thus observational evidence that thermal emission from a pure hydrogen photosphere contributes to – and perhaps dominates – the NS luminosity at photon energies of 0.1–1 keV. This will be tested much better with upcoming *Chandra* and *XMM-Newton* observations.

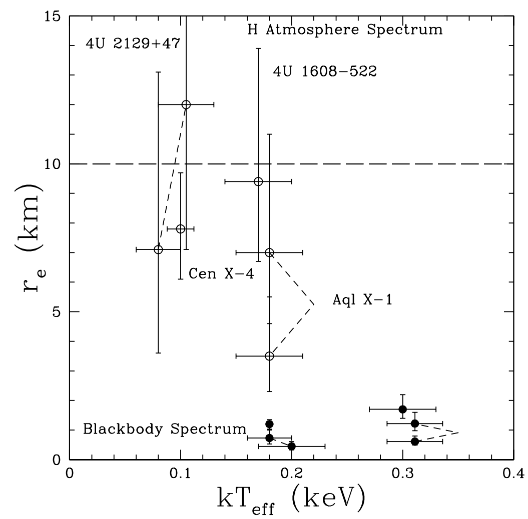

Figure 2. Comparison between the spectral parameters r_e and $kT_{\rm eff}$, derived from spectral fits of the quiescent X-ray emission from Aql X−1, Cen X−4, 4U 1608−522 and 4U 2129+47. The *open points* are for the H atmosphere spectrum and the *solid points* are from a black-body spectrum. The two points connected for Aql X−1 correspond to the upper- and lower- distance limits for that source. The two connected points for 4U 2129+47 are for two different distance/$N_{\rm H}$ estimates. The H atmosphere fits produce values of r_e, consistent with a 10 km NS. From Rutledge et al. (2000).

4. What Powers the Quiescent Emission from the Neutron Stars?

In our earlier discussion of black holes, we pointed out that the expected coronal X-ray emission from the tidally locked and rapidly rotating stellar companions is at a level consistent with that observed from the black hole transients A 0620-00 and GRO J1655-40 (though see Lasota 2000 for an argument against this). The BH transient V404 Cygni is too bright to be explained this way, as are all binaries containing NSs. Several energy sources for the quiescent NS emission have been discussed and developed (Stella et al. 1994). These include late-time thermal emission from heat released deep in the NS crust during outbursts (Brown et al. 1998), accretion (Van

Paradijs et al. 1987; Menou et al. 1999), and non-thermal emission from a turned-on radio pulsar (Campana et al. 1998a).

4.1. THERMAL EMISSION FROM DEEP NUCLEAR ENERGY RELEASE

Brown, Bildsten and Rutledge (1998) showed that the "rock-bottom" emission from these systems is set by thermal emission from the neutron star. This minimum luminosity comes from nuclear energy deposited in the inner crust (at a depth of ≈ 300 m) during the large accretion events. The freshly accreted material compresses the inner crust and triggers nuclear reactions that deposit about an MeV per accreted baryon there (Haensel & Zdunik 1990). This heats the NS core on a 10^4-10^5 yr timescale, until it reaches a steady-state temperature $\approx 4 \times 10^7 (\langle \dot{M} \rangle / 10^{-11}\, M_\odot\, \mathrm{yr}^{-1})^{0.4}\,\mathrm{K}$ (Bildsten & Brown 1997), where $\langle \dot{M} \rangle$ is the time-averaged accretion rate in the binary. A core this hot makes the NS "glow" at a luminosity

$$L_q \approx \frac{1\,\mathrm{MeV} \langle \dot{M} \rangle}{m_p} \approx 6 \times 10^{32} \frac{\mathrm{erg}}{\mathrm{s}} \left(\frac{\langle \dot{M} \rangle}{10^{-11} M_\odot\, \mathrm{yr}^{-1}} \right), \tag{1}$$

even after accretion halts (Brown et al. 1998). The NS is then a thermal emitter in quiescence, consistent with the inferrences from the quiescent spectroscopy noted earlier. This quiescent emission is inevitable (unless accelerated core cooling mechanisms are active in these stars that do not seem to occur in young neutron stars) and provides a "floor" for the quiescent luminosity. Additional emission mechanisms can add to this, increasing the luminosity and modifying the spectral shape.

In exploring this scenario Rutledge et al. (2000) analysed only observations made during periods of the lowest observed flux, to minimize contributions from accretion. They calculated the bolometric luminosity from the H atmosphere fits. Using these new bolometric quiescent luminosities for Aql X-1, Cen X-4, and 4U 1608−522, they plotted (Fig. 3) L_q/L_o as a function of t_r/t_o (Brown et al. 1998). Here L_q and L_o are the observed quiescent and average outburst luminosities, and t_r and t_o are the recurrence interval and outburst duration. We show this relation for the NSs (*open circles*) Aql X-1, Cen X-4, 4U 1608−522, and EXO 0748−676 and the BHs (*filled circles*) H 1705−250, 4U 1543−47, Tra X-1, V 404 Cyg (GS 2023+33), GS 2000+25, and A 0620−00. We denote with an arrow those BHs for which only an upper limit on L_q is known.

The expected incandescent luminosity is plotted for two amounts of heat per accreted baryon deposited in the inner crust during an outburst: 1 MeV (*solid line*) and 0.1 MeV (*dotted line*). With the exception of Aql X-1, Cen X-4, 4U 1608−522, and the Rapid Burster, the data from this plot is taken from (Chen et al. 1997). For Aql X-1 and the Rapid Burster, L_o

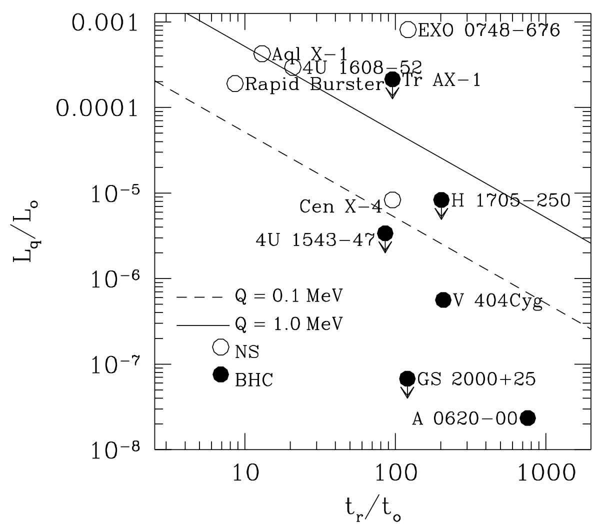

Figure 3. The ratio of quiescent luminosity L_q to outburst luminosity L_o as a function of the ratio of recurrence interval t_r to outburst duration t_o. The lines are for different amounts of heat, 0.1 MeV (*dashed line*) and 1.0 MeV (*solid line*), per accreted nucleon deposited at depths where the thermal time is longer than the outburst recurrence time. Also plotted are the observed ratios for several NSs (*open circles*) and BHs (*filled circles*). For most of the BHs, only an upper limit (*arrow*) to L_q is known. Data is from (Chen et al. 1997), with the exception of L_q for the Rapid Burster (Asai et al. 1996b). For Aql X-1 and the Rapid Burster, L_o and t_o are accurately known (*RXTE*/All-Sky Monitor public data); for the remaining sources L_o and t_o are estimated from the peak luminosities and the rise and decay timescales. From Rutledge et al. (2000).

and t_o are accurately known (*RXTE*/All-Sky Monitor public data); for the remaining sources L_o and t_o are estimated from the peak luminosities and the rise and decay timescales.

Four of the five NSs are within the band where the quiescent luminosity is that expected when the emitted heat is between 0.1-1.0 MeV per accreted baryon. The fifth NS (EXO 0748−676), has a higher quiescent luminosity (by a factor of 10), which we interpret as being due to continued accretion, an interpretation which is reinforced by the observation of spectral variability during the quiescent observations with *ASCA* (Corbet et al. 1994; Thomas et al. 1997), on timescales of ∼1000 sec and longer. (Garcia & Callanan 1999 measured L_x=1×10^{34} erg s^{-1} from Einstein/IPC observations of this source.) The BHs on this figure are more spread out across the parameter-space, qualitatively indicating a statistical difference – although not one which is particular for each object – between the two classes of objects. This suggests the NS quiescent luminosity is more strongly related to the accreted energy than the BH quiescent luminosities.

4.2. ACCRETION ONTO THE NEUTRON STAR DURING QUIESCENCE

Accretion was initially suggested (Van Paradijs et al. 1987) as the energy source of quiescent emission from transiently accreting NSs, partially because few other emission mechanisms were known at the time. Thermal emission was not considered, as it was presumed that these neutron stars with low-mass companions were clearly older than the NS core cooling timescale (10^6 yr) and would have cold cores. The work of Brown et al. (1998) changed that.

There are presently no observational results which exclude the possibility that part of the quiescent luminosity of these NSs is due to accretion. Indeed, some observational evidence suggests that accretion occurs onto the NS surface during quiescence; long-term (months-years) variability in the observed flux has been reported (a factor of 4.2 ± 0.5 in 8 days from Cen X$-$4; Campana et al. 1997) and in 4U 2129+47, by a factor of 3.4 ± 0.6 between Nov-Dec 1992 and March 1994; Garcia & Callanan 1999; Rutledge et al. 2000). If so, then the required rate is about $\dot{M}_q = 10^{-14}$–10^{-15} $M_\odot$ yr^{-1}, a factor of 10^{-4} below the time-averaged rate. While this intensity variability can be explained by a variable absorption column depth, active accretion during quiescence is also a possibility.

Recent observations of Aql X$-$1 at the end of an outburst showed an abrupt fading into quiescence (Campana et al. 1998b) associated with a sudden spectral hardening (Zhang et al. 1998a). This was followed by a period of ~ 15 days, over which the source was observed (three times) with a constant flux level (Campana et al. 1998b). This behavior was interpreted as the onset of the "propellor effect" (Illarionov & Sunyaev 1975; Stella et al. 1986) in this object, which would inhibit – perhaps completely – accretion onto the NS. The energy source for the long-term nearly constant flux is most likely thermal emission (Brown et al. 1998).

A thermal spectrum alone cannot distinguish between accretion and a hot NS core as the energy source. This is because the accretion energy is likely deposited deep beneath the photosphere and is re-radiated as thermal emission (Zampieri et al. 1995). This emission is nearly identical to that expected from the hot NS core. The only possible difference would be if the accretion rate is high enough (about $> 10^{-13} M_\odot$ yr^{-1}, see footnote in § 3), to constantly replenish metals in the photosphere and if spallation of these elements is not too strong (Bildsten et al. 1992). These metals, particularly Oxygen, will imprint photoabsorption edges in the emergent spectrum (Rajagopal & Romani 1996). The presence of such metallic absorption in the NS quiescent emission spectra – aside from being astrophysically important – would clearly indicate active accretion onto the NS.

4.3. MAGNETOSPHERES AND SPINS

Evolutionary scenarios that connect the accreting neutron stars in Low-Mass X-ray Binaries to millisecond radio pulsars predict that these neutron stars should be rapidly rotating (at a few milliseconds) and magnetized at $10^8 - 10^9$ G. There is only one transiently accreting neutron star that unambiguously looks like this, SAX J1808.4-3658, at $\nu_s = 401$ Hz (Wijnands & Van der Klis 1998; Chakrabarty & Morgan 1998), and $B = 10^8 - 10^9$ G (Psaltis & Chakrabarty 1999). We know little about the magnetic fields and spins of the neutron stars in the other transients. The only one for which we know the spin is Aql X-1, where nearly coherent oscillations during Type I bursts imply a rotation rate of 550 Hz (Zhang et al. 1998b).

The neutron star's spin and magnetic field are important for two reasons. The first is the distinct possibility of shutting off accretion onto the neutron star from the "propellor" effect. This can happen when the magnetospheric radius exceeds the co-rotation radius (where the Kepler period equals the spin period), which for a neutron star spinning at ν_s with magnetic moment μ, will happen when the accretion rate is below $\dot{M}_p \approx 7 \times 10^{-11} M_\odot \ \mathrm{yr}^{-1} (\mu/10^{26}\mathrm{G\ cm}^3)^2 (\nu_s/300\ \mathrm{Hz})^{7/3}$, suggesting a minimum accretion luminosity of $\approx 10^{36}$ erg s^{-1} for the fiducial parameters in the accretion rate equation. Even once in this regime, Campana et al. (1998a) discussed the possibility of emission from the gravitational energy release of matter striking the magnetosphere itself, which would yield a lesser amount of energy per gram and thus a lower total luminosity. Finally, if a magnetic field plays an important role in the geometry of quiescent accretion, one might expect some asymmetries that would produce X-ray pulsations. This was not observed in the recent fading of Aql X-1 (Campana et al. 1998b; Zhang et al. 1998a), where stringent limits on the pulsed fraction of the emission were placed ($\leq$1.2% rms variability, 95% confidence; Chandler & Rutledge 2000) at a time believed to be just at the onset of the propellor for a 10^8G field. What this implies about the magnetic field strength of Aql X-1 is still unknown.

The second place where the magnetic field and spin matter is when the magnetosphere becomes larger than the light cylinder. One might imagine the neutron star turning into a millisecond radio pulsar at this stage (see Stella et al. 1994 for an overview). However, a millisecond radio pulsar at the position of a transient X-ray binary has never been observed, even for SAX J1808.4-3658. Perhaps it is difficult for the accretion rates in these systems to become low enough to allow pulsar activity.

Campana et al. (1998b) conjectured that the hard X-rays sometimes seen in quiescence might be non-thermal emission from an active pulsar. If so, then the energy source is a fraction of the spin-down luminosity. As

Stella et al. (1994) noted, if the fraction of spin-down energy going into X-rays in transiently accreting binaries is similar to that observed from millisecond radio pulsars ($L_x \approx 10^{-3}\dot{E}$; Becker & Trümper 1999), and the magnetic field strengths are sufficient to "turn on" a millisecond pulsar, then the predicted X-ray luminosities are close to those observed ($\sim 10^{32}$-10^{33} erg s^{-1}). Indeed, a few of the X-ray detected millisecond pulsars have X-ray luminosities in this range (Becker & Trümper 1999). Brown et al. (1998) noted the same possibility for the neutron star in SAX J1808.4-3658. The X-ray spectral energy distribution of such a non-thermal component is hard and power-law like (Becker & Trümper 1999) similar to the hard power-law tails observed in Cen X-4 and Aql X-1 (Asai et al. 1996b; Campana et al. 1998b).

5. Conclusions and The Future

It is only recently that the focus of studying quiescent NSs has changed from parameterizing the phenomenology, to measuring the physics behind the emission. Higher quality X-ray data from the X-ray spectroscopy missions *Chandra*and *XMM-Newton* will provide much better data than any of the previous missions. These will also provide the means to account for possible contributions due to a hard-power law component in the black holes, as well as the neutron stars.

Bildsten and Rutledge (2000) have recently argued that two (A0620−00 and GRO J1655−40) of the three X-ray detected black hole binaries exhibit X-ray fluxes entirely consistent with coronal emission from the companion star. The current upper limits on the remaining BHs are also consistent with production via chromospheric activity in the secondary. All four NSs (Aql X−1, Cen X−4, 4U 1608−522, 4U 2129+47) have quiescent X-ray luminosities which are at least ten times greater than expected from chromospheric emission alone.

This suggests that a viable hypothesis for the majority of the transient NSs and BHs is that little accretion occurs in quiescence. Though mass is continuously transferred from the companion to the outer accretion disk (as is clear from the Hα line emission), accretion onto the compact object appears to be small. In the absence of accretion, the quiescent X-rays from a NS would then be dominated by thermal flux from a hot NS core (Brown et al. 1998), while for BHs, the quiescent X-rays come from the chromospheric activity of the secondary. The advantage of this hypothesis is that it explains the X-ray luminosities of BHs and (separately) NSs, without having to invoke dramatically different quiescent accretion rates that depend on the type of compact object (Menou et al. 1999).

At odds with this simple scenario is the detection of X-rays from V404

Cygni at a level which is a factor of ten brighter than can be explained as coronal emission. In addition, the observed variability in the NS quiescent luminosity can not be explained easily without some accretion. Both of these observations point to the possibility that the transferred matter sometimes can make it down to the central compact object. The fraction of the time this occurs and the reason why still needs to be better understood.

One of the most important areas of research in the coming years will be the search for and exploitation of photospheric absorption edges in NS quiescent spectra (§ 4.2). These edges are a kind of "holy grail" of NS spectroscopy as the known energy permits us to measure the gravitational redshift. We can also use realistic atmospheric spectra to derive the emission area radius divided by the distance to the NS. This radius, combined with the photospheric redshift, will provide an independent measure of the NS mass and radius, and thus its equation of state. The major uncertain parameter in these systems – the source distance – can be measured with the Space Interferometric Mission, set for launch in 2006, which will measure parallactic distances to objects as faint as 20th magnitude to 4μarcsec; which can find the majority of systems in this review.

In addition to better understanding of known sources, we hope that the new satellites will also probe quiescent emission from other populations of transient accretors. A likely place for progress with *Chandra* are the low-luminosity X-ray sources observed in globular clusters (Hertz & Grindlay 1983) which are either cataclysmic variables (Cool et al. 1995; Grindlay et al. 1995) or transient neutron stars in quiescence (Verbunt et al. 1984). X-ray spectroscopy can identify these objects as NSs radiating thermal emission from the atmosphere, or imply a different origin for the emission. As discussed above and elsewhere (Brown et al. 1998), the quiescent luminosities of these sources are set by the time averaged accretion rate. Thus, the low luminosity (10^{31} erg s^{-1}) X-ray sources in globular clusters, if they were transient neutron stars in quiescence, would have $\langle \dot{M} \rangle \approx 2\times10^{-13}\ M_\odot$ yr^{-1}. The advantage to the cluster work will be the prior knowledge of the distance and reddening to the sources. *Simultaneous thermal spectroscopy of multiple sources in the same globular cluster at a known distance might well provide the first unambiguous and simultaneous measurements of many neutron star radii!*

We also expect progress in quiescent observations of transiently accreting X-ray pulsars. These systems are typically in high mass ($\gtrsim 10 M_\odot$) X-ray binaries, where the companion can contribute a significant fraction of the expected persistent X-ray luminosity, forcing us to depend on a pulse for secure detection of thermal emission in quiescence. The high magnetic fields (10^{12}–10^{13} G) perturb the opacity of the NS atmosphere and produce a pulse even if the underlying flux is uniform. Pulsations at the same luminosity level (10^{32} erg s^{-1}; cf. Eq. 1) as observed from the low-magnetic field systems was recently seen from A 0535+26 at a time when the circumstellar disc was absent (Negueruela et al. 2000). After excluding a magnetospheric origin, this pulsed emission was interpreted as due either to matter leaking onto the polar caps or to thermal emission from the NS core (Negueruela et al. 2000) – heated from nuclear emission deposited in the inner crust during the accretion outbursts, as described by Brown et al. (1998).

In binaries containing black holes, the major observational challenge is to distinguish between the ADAF and stellar coronal emission models. The best test is likely to be high S/N X-ray spectroscopy in the 0.1-4 keV range, where spectral lines contribute significantly in Raymond-Smith plasma (coronal) models, but not in ADAFs (Narayan & Raymond 1999). Once this is done, more focused studies of the accretion flows around black holes can be carried out.

We are clearly at the forefront of discovery regarding the physics of the quiescent emission of neutron stars and black holes. We have moved beyond initial detection, and at present a variety of mechanisms have been proposed to explain emission from both black holes and neutron stars. In the present era of *Chandra* and *XMM-Newton*, we will study these emission mechanisms in detail for the brightest of sources. The opportunity to detect neutron star photospheric absorption edges, and the ability to measure the neutron star radius from the broad-band spectroscopy may well constrain the neutron star equation of state.

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